VAPORIZATION OF DROPLETS IN PREMIXING CHAMBERS

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by

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20. Abstract

Detailed measurements have been made of the structures of turbulent fuel sprays vaporizing in heated airstreams. The measurements show the size dependent vaporization and dispersion of the droplets and the important influence of the large eddies in the turbulence. The measurements form a data base for the development of models of fuel spray vaporization. Two laser techniques were specially developed for the investigation. A laser tomography technique converts line-of-sight light scattering measurements into time averaged 'point' measurements of droplet size distribution and volume concentration. A laser anemometer particle sizing technique has been further developed to permit accurate measurements of individual particle sizes and velocities, with backscatter collection of light. The experiments are combined with heat transfer models to analyse the performances of miniature thermocouples in liquid sprays.

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SUMMARY

Measurements have been made of turbulent fuel sprays vaporizing in heated airstreams. Two new, laser-based, diagnostic techniques have been developed for making these measurements. A laser tomography technique converts the measured scattered light from a laser beam scanning different parts of a spray, to provide point measurements of droplet size distribution and volume concentration. The technique is analogous to that used by X-ray brain scanners to derive two-dimensional information on internal structure from line-integral measurements. Comparison with narrow depth of field spark photomicrography shows the accuracy of the tomography technique and the technique is shown to provide a rapid means of characterizing internal spray structure. Developments of a Laser Doppler Anemometer particle sizing technique have been made. This enables the simultaneous measurement of particle sizes and velocities. Tailoring of the laser light intensity distribution in the measurement volume, and an advanced Mie theory light scattering computer programme for large particles, permit accurate measurements using backscatter light collection. These techniques are combined with miniature thermocouples and photography to make detailed measurements of vaporizing kerosene spray structure as a function of the temperature of the surrounding air flow. These measurements show the preferential vaporization of the smaller droplets (leaving a residue of larger droplets), size-dependent dispersion of droplets by the turbulence and the important influence of the coherent large eddies in the turbulence. The experiments are designed with carefully controlled and measured initial and boundary conditions and they thus form a data base for developing computer models of spray vaporization. The experiments reveal useful information on the performances of miniature thermocouples in liquid sprays. Heat transfer models are used, with the experimental data, to elucidate the effect of spray density on the recorded temperature and response characteristics of a thermocouple.

INTRODUCTION

This investigation has the objective of deriving fundamental data on the vaporization of liquid fuel sprays injected into heated airstreams. The investigation is relevant to the development of lean premixed/prevaporized combustors and it was thus linked with the NASA Lewis 'Stratospheric Cruise Emission Reduction Programme' (SCERP). In addition the data derived from these experiments are directly relevant to many other practical combustion and non-combustion systems which utilize liquid sprays. The experiments are designed to give axisymmetric sprays with controlled and known initial and boundary conditions. In this way they act as a data base for the development and testing of computer models for the prediction of spray ballistics and vaporization in a turbulent high temperature environment. An integral part of this investigation has been the development and refinement of diagnostic techniques for the rapid, accurate and high resolution measurement of internal spray structure. The measurements completed included local droplet sizes and velocities and the local gas velocity and temperature in various sprays. The emphasis of the investigation is on high temporal and spatial resolution measurements of the internal spray structure, as it vaporizes in a hot turbulent environment, rather than on global measurement of total vaporization as a function of initial conditions. Most of the results of this two year programme have been given in various reports, papers and conference

presentations. Thus an outline of the results of the investigation and an overall view of the project is given below and reference should be made to the relevant publications for detailed information.

Outlines are first given of work accomplished in the development of new measurement techniques, and in the refinement of existing techniques, to permit measurements in vaporizing sprays. The main spray experiment is then described. The results of the experiment are discussed and the future extension of this work is also outlined.

MEASUREMENT TECHNIQUES FOR VAPORIZING FUEL SPRAYS

Ideally, it is required to make 'point' measurements, within turbulent, polydisperse fuel sprays in heated gas streams, of the following quantities: gas velocity (mean and fluctuating); droplet velocity; droplet diameter; gas temperature (mean and fluctuating); local vaporization rate; droplet temperature; droplet concentration and volume flux.

Measurement of the droplet characteristics (apart from temperature) have frequently been made in the past by using imaging techniques such as photography and holography. However these techniques are extremely time consuming and this precludes the detailed mapping of various sprays, which is required for this study. Thus rapid laser light scattering techniques have been developed and utilized in this investigation, for the measurement of liquid-phase characteristics. The miniature fine wire thermocouple remains the most reliable technique for measuring mean and fluctuating temperatures in gas flows. The thermocouple has particular problems in two-phase flows, and these have been analyzed as part of this project.

Laser Tomography

Particle size distributions have been determined using a new development of the Malvern Instruments ST1800 Particle Size Meter. A parallel He/Ne laser beam is passed through the spray and the forward scattered light is collected by a Fourier transform lens. The radial light power distribution is measured using a photodetector consisting of 30 concentric annulli placed in the focal plane of the lens, and the particle size distribution is calculated from this by using Fraunhofer diffraction theory. Total particle concentration is determined by measuring the total forward scattered light power.

This instrument rapidly gives an 'overall' size distribution for a complete width of the spray. The line-integral nature of the particle size distribution does not give any information on the drop size distribution at any point within the spray. However, if a number of line integral measurements are made through different parts of the spray, the scattered light data can be transformed into two-dimensional distributions of drop size distribution and concentration in a plane through the spray. This data transformation is termed 'tomography' and has been applied to several systems in recent years, particularly for medical X-ray brain and body scanners. For the case of an axisymmetric system, such as the sprays studied here, the transformation is greatly simplified; only one set of parallel scans through the spray being

required (this is analogous to the Abel transformation used in flame spectroscopy studies). Full details of the procedure are given in a recent paper.[1] The results of the investigations in vaporizing fuel sprays by using this technique are described in References 2, 3 and 4.

Measurements using this technique have been compared with size distributions measured at the same positions, in the same sprays, by the computer analysis of spark photographs. The agreement is excellent. The laser tomographic technique has been shown to give rapid and accurate measurements of the local size distributions and volume concentrations of droplets in sprays and it is thus ideal for the present purposes. Work has also been in progress examining the extension of this technique to spray flames and to dense sprays. Such extensions are found to be theoretically possible, but further development work is required.

Light Scattering Theory and Laser Doppler Anemometry (LDA)

Prior to this investigation the authors had demonstrated the feasibility of measuring both the sizes and velocities of droplets as they traversed the measurement volume of an LDA system. It was shown that this could be achieved by a pulse height analysis of the signal pedestals. During the course of the present investigation, work on this technique has concentrated on improving its accuracy and range of applicability to permit the reliable mapping of the vaporizing fuel sprays. Two significant improvements have been developed:
(1) the extension of the technique to backscatter collection of light;
(2) tailoring the light distribution in the measurement volume to improve accuracy and reduce data analysis time.

To prove the validity of using backscatter light collection to measure particle sizes, it was necessary to improve the existing light scattering analysis. This analysis was used to predict the dependency of the LDA signal peaks on the particle sizes. Working with a group at Rouen University (France) Mie theory computations were extended to particle diameters larger than 100 μm.[5] For forward scattering there was found to be reasonable agreement with the predictions of the geometric optics theory, which has been used previously by the authors for the prediction of LDA signals. However the geometric optics analysis could not be used reliably for the prediction of the backscattered light. The new Mie theory computations permit the prediction of the collected light in the backscatter direction and through a given collection aperture. It is found that monotonic signal amplitude/particle size relationships could be produced, thus showing that a backscatter LDA system can be used to measure both the sizes and the velocities of droplets.

An additional difficulty with the original LDA particle sizing technique was introduced by the dependency of the signals upon the trajectory of the particles within the measurement volume. This was caused by the Gaussian light intensity distribution across the laser beam. This difficulty has been minimized by tailoring the light distribution by using a suitable combination of beam expanders, lenses and filters.

Thermocouples

The authors have developed a technique using on-line computer controlled

miniature thermocouples for measurements, originally, in gas flames. The technique has been extended and has also been used in the present spray experiments. Incidental to the main work, the measurements and accompanying analyses have produced original and interesting information on the accuracy of miniature thermocouple measurements and upon the effects of droplet impaction on the recorded temperatures and thermocouple response.[6, 7]

A heat transfer analysis has been used to model the influence of droplet impaction on the temperature recorded by the thermocouple and also the effect on the response characteristics (measured by an electrical square wave, overheating technique). The analysis has been checked by using the thermocouple measurements in the sprays, and reasonable agreement was found. It was found that droplet impaction significantly changed the measured mean temperature of the thermocouple, so that it differed significantly from the gas temperature even in dilute sprays.[7] However, up to a limiting concentration of droplets, the true mean gas temperature can be estimated from the measured temperature provided that the local volume flux of droplets and droplet temperatures are known.

It is found that, even in quite dense sprays, the local mean gas velocity can be calculated accurately from the local response characteristics of the thermocouple. Excellent agreement was found between velocities derived from the thermocouple response and those measured by LDA.

EXPERIMENT

Apparatus

During the period of development of the measurement techniques, various spray rigs were utilized. The principal series of measurements were made in a twin-fluid atomized kerosene spray. This apparatus and atomizer are described in detail in Reference 2. The spray was axisymmetric and the surrounding secondary airstream was also axisymmetric. This secondary flow had a uniform velocity distribution, at the atomizer plane, and a low turbulence level. The first 150 mm length of spray was investigated by traversing the spray relative to the fixed measurement probes. The secondary air could be preheated electrically up to 500 K. Typically up to at least 70 per cent of the spray, by volume, had vaporized within the length under investigation.

Results and Discussion

The initial and boundary conditions of the sprays were carefully measured to permit later comparisons with computer model predictions of the flows. These measurements included the initial droplet size distributions, within a few mm of the atomizer under cold conditions, the initial velocity and temperature distributions in the secondary air flow and the velocity and temperature of the secondary air as a function of distance downstream.

As described in Reference 2, measurements of droplet sizes, velocities and concentrations and gas velocity and temperature, were made in sprays with

differing secondary flow temperatures. Furthermore, measurements were made, without kerosene, but with the secondary and atomizing air flows. This gave information on the relative influence of the droplets on the structure of the turbulent air flow. For the particular sprays that have been studied it was found that momentum transfer from the air to the liquid phase was relatively insignificant compared with the total initial momentum of the atomizer flow. This permits the simplifying assumption that the gas flow field is not greatly influenced by the presence of droplets, for these sprays. The measurements[2] demonstrated the preferential vaporization of the smaller droplets, leaving a residue of larger droplets. Liquid phase isoconcentration contours were constructed for vaporizing sprays with different secondary air temperatures. At cold temperatures vaporization rate was low and the radial concentration distribution remained Gaussian in shape, with a central peak which fell as (distance downstream)$^{-1}$, which would be expected for a passive scalar in a self-preserving jet. For the hot cases, this dependency was not found and there was seen to be a very rapid vaporization of the smallest droplets very near the atomizer followed by a more gradual vaporization of the remainder of the spray. Vaporization was typically accompanied by narrowing of the droplet size distribution and an increase in the mean droplet diameter. The measurements also indicated the size-dependent acceleration of droplets to reach, approximately, the local gas velocity in the first 100 mm of spray. The thermocouple measurements showed the existence of significant 'heat up' times for the droplets in the initial part of the spray, before they reached the equilibrium (wet bulb) temperatures.

The measurements and the flow visualizations clearly showed the importance of size-dependent dispersion of droplets by the turbulence. In particular large, energetic eddies could be seen to be the dominant mechanism for the diffusion and dispersion of droplets in the sprays. For the particular sprays which have been investigated, the larger droplets tended to be dispersed to the outer part of the sprays and there was typically a very dilute, almost monosize, layer of larger droplets at the extreme peripheries of the sprays.

Concluding Remarks and Future Work

1. Laser based measurement techniques have been developed and improved to provide accurate, rapid and high resolution measurements in vaporizing fuel sprays.

2. Data have been derived describing the detailed structures of turbulent vaporizing fuel sprays, at different temperatures for the surrounding airstream.

3. The measurements show that prediction of turbulent, vaporizing sprays requires the inclusion of models of the size-dependent dispersion of droplets by the turbulence. Furthermore the dependency of vaporization and ballistics on the relative droplet/gas velocity and the local droplet environment should be modeled.

4. In the future extension of this project, the data will be compared with the predictions of computer models, with the objective of improving the accuracy of these models.

5. The new experiments will concentrate on the droplet size dependent effects and on the turbulence effects, in the vaporizing sprays, which have been shown to be important. This will involve measurements of local fluctuating spray quantities and cross-correlations, for example between local droplet density, gas temperature and velocity.

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